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WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT

NO. WAL 710/576

Effect of Directional Properties on Rolled Homogeneous Armor

BY

E. L. REED
Research Metallurgist

DATE 6 January 1944

WATERTOWN ARSENAL
WATERTOWN, MASS.

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Watertown Arsenal Laboratory

Memorandum Report WAL 710/576

Final Report on Problem B-2.8

6 January 1944

Effect of Directional Properties on

Rolled Homogeneous Armor

1. As requested by The Proving Center, Aberdeen (APG 470.5/7436 - Wtn 470.5/6587(r)) and Tank Automotive Center (TAC 451.25/2-241 - Wtn 470.5/5734(r)), metallurgical examination has been completed on samples of eighteen (18) 1½" thick "straight-away" rolled plates manufactured by the Great Lakes Steel Corporation. The plates were heat treated similarly to approximately the same Brinell hardness range and all plates were from heat number 9-13945. Ballistic tests are reported in Armor Test Report AD-555. The plates were tested as a part of a program at The Proving Center to compare the shock resistance of cross rolled armor with that of "straight-away" rolled armor. This particular phase of the test covered only the testing of "straight-away" rolled armor. When cracking occurred in the ballistic test, these cracks always followed the direction of rolling. This fact indicates that this type of armor has less resistance to shock in that direction.

2. Metallurgical tests indicated that the direction of rolling was incorrectly designated by the manufacturer on plates numbers 5AX, 3B, 1D, 4C, 4, 5, 1, 2B, 3D. With the exception of plates numbers 2C, 2B, 3B, and 1D, the plates were of satisfactory steel quality. Apparently these four plates which had a "D" fracture were rolled from the segregated portion of the ingot. All plates with the exception of plate number 1 had a fibrous fracture, indicating that the balance of the plates were satisfactorily heat treated. This characteristic was associated with a microstructure of essentially tempered martensite with traces of intermediate temperature transformation products.

Hardness surveys indicated the center of twelve plates to have a Brinell hardness of 281-289, which was some 20 points higher than that reported by the manufacturer on the surface of the plates and which in some cases was some 12-16 points higher than that obtained near the surface at this arsenal. Apparently, in several instances, the manufacturer did not remove all the decarburization on the surface of the plates previous to the hardness determinations. The relatively higher hardness at the center of some of the plates was correlated with an increase in the yield strength as compared with these values determined halfway between the center and surface

of the plate. There was no marked variation in the hardness or the tensile properties from plate to plate.

Generally speaking the directional properties as determined by the differences between percentage elongation and reduction of area in the longitudinal and transverse directions were more pronounced in the plates of the poorest steel quality.

3. Metallurgical examination consisted of the following tests:

a. Fracture Tests for Steel quality.

b. Brinell Hardness Surveys.

c. Tensile Tests taken in the longitudinal and transverse directions of samples from the center and halfway between the center and the surface.

d. Microscopic Examination

4. The results of the above tests in detail are presented below:

a. Fracture Tests for Steel Quality.

Samples 8" x 3" in size cut from the longitudinal and transverse sections were notched transversely to the long dimension to a depth of approximately 3/4" on both sides and broken slowly under a forge press. The results of these tests are given in Table 1. Apparently plates 2C, 2B, 3B and 1D were rolled from segregated portions of the ingot since these plates showed evidence of excessive laminations in the fracture. The balance of the plates were relatively free from these defects. Plate No. 1 showed evidence of crystallinity in the fracture while the balance of the plates were all fibrous, as broken under the slow rate of load application by the press.

b. Brinell Hardness

The results of the Brinell hardness tests are given in Table II. In general, the Brinell hardness values reported by the manufacturer were lower than those obtained at this arsenal. Plate No. 1, which was improperly quenched as revealed by its partially crystalline fracture, had the lowest hardness of the series. The balance of the plates were fairly uniform in hardness, that is, from plate to plate and also along the cross section of each plate.

c. Tensile Tests

The results of the tensile tests are shown in Table III. In general, the directional properties of the "straight-away" rolled material were reflected by the physical properties obtained in the longitudinal and transverse directions. This was particularly true in the case of the

poor quality plates.

The relative higher hardness reported at the center of some of the plates as compared to that near the surface was correlated in some cases with an increase in the yield strength values. Otherwise, no particular variation was detected in the physical properties made at the center and at halfway between the center and surface of the plates.

Fracture Tests and Tensile Tests show that the direction of rolling was incorrectly indicated by the manufacturer on plates numbers 5AX, 3B, 1D, 4C, 4, 5, 1, 2D, 3D.

d. Microscopic Examination

Figures 1-3 inclusive illustrate the average amount of non-metallic inclusions present in the plates. Several bands of aluminum oxide were present in plate XA. The balance of the plates contained fine elongated non-metallics associated in many cases with zirconium nitride.

Figures 4-6 inclusive illustrate the typical microstructure of the samples. With the exception of plate numbers 1 and 1D all plates exhibited a tempered martensitic structure, consisting of sorbite and some traces of ferrite. The microstructure of plate No. 1 consisted of considerable amounts of ferrite and sorbite while plate No. 1D showed evidence of intermediate temperature transformation products.

Note: Photomicrographic work done by M. Yoffa.

5. Metallurgical examination indicated that, in general, the plates were satisfactorily heat treated but in some cases were rolled from the segregated portions of the heat which resulted in inferior steel quality.

E. L. Reed.

E. L. REED
Research Metallurgist

APPROVED:

N. A. MATTHEWS
Major, Ord. Dept.

TABLE I

FRACTURE TESTS

Plate No.	Fracture Parallel to Rolling Direction	Fracture Perpendicular to Rolling Direction	
3	C	C	
AA	C	C	
1C	B	C	
6	B	B	
5A	D	D	
2C	C	D	
5	C	D	
6A	B	C	
4C	C	C	
4	B	C	
5AX	C	C	
6C	B	B	
1	B	B	Crystallinity at center of fracture.
2B	D	D	
3D	B	B	
2	D	D	
3B	D	D	
1D	C	D	

TABLE II

Brinell Hardness

Plate No.	Reported by Manufacturer		Reported by Watertown Arsenal Cross Sectional Values					
	Face	Back	Near Face	Av.	Center	Av.	Near Back	Av.
3	262	262	269-277	273	277-293	285	277-285	281
AX	262	262	277-277	277	262-262	262	269-277	273
1C	262	262	277-277	277	262-269	266	269-277	273
6	262	269	285-285	285	285-293	289	277-285	281
5A	262	269	269-277	273	285-285	285	285-285	285
2C	269	269	277-277	277	285-285	285	277-285	281
5	262	262	262-277	270	269-285	277	269-277	273
6A	262	262	277-277	277	269-277	273	277-277	277
4C	262	262	269-269	269	262-269	266	262-269	266
4	262	262	277-277	277	277-285	281	269-277	273
5AX	262	262	269-277	273	285-285	285	285-285	285
6C	262	262	269-277	273	277-285	281	269-285	277
1	262	262	255-262	259	269-277	273	255-262	259
2B	269	262	269-269	269	277-285	281	269-285	277
3D	262	262	262-269	266	277-285	281	262-269	266
2	262	262	269-269	269	285-285	285	277-277	277
3B	262	252	269-269	269	277-285	281	269-285	277
1D	262	262	269-285	277	277-285	281	269-277	273

TABLE III

TENSILE TESTS

Test Bar .357" Diameter

Plate No.	Location of Test Specimen	Direction	Yield Strength Lbs/sq in	Tensile Strength Lbs/sq in	% Elong.	% Red Area	Average Cross Section of Brinell Hardness Near Face	Center	Near Back
3	Midwall*	Longitudinal	114,000[1]	134,500[1]	17.9[1]	64.1[1]			
3	Midwall	Transverse	112,000	134,600	15.4	50.0			
3	Center	Longitudinal	117,000	136,500	18.3	61.5	273	285	281
3	Center	Transverse	117,500	137,300	15.7	45.3			
XA	Midwall	Longitudinal	109,000	130,400	18.6	63.7			
XA	Midwall	Transverse	108,000	131,800	15.4	50.2			
XA	Center	Longitudinal	105,500	124,300	19.3	66.7	277	262	273
XA	Center	Transverse	105,500	125,000	17.5	54.5			
1C	Midwall	Longitudinal	115,000	133,100	18.6	63.7			
1C	Midwall	Transverse	111,500	132,100	16.1	51.8			
1C	Center	Longitudinal	109,000	131,300	18.6	65.0	277	266	273
1C	Center	Transverse	112,500	133,300	17.1	53.1			
6	Midwall	Longitudinal	116,500	136,900	18.3	62.7			
6	Midwall	Transverse	114,000	136,000	16.1	50.0			
6	Center	Longitudinal	119,500	136,800	18.6	63.2	285	289	281
6	Center	Transverse	116,500	135,800	16.4	51.9			
5A	Midwall	Longitudinal	106,500	135,100	19.0	63.4			
5A	Midwall	Transverse	114,000	135,600	14.7	49.4			
5A	Center	Longitudinal	115,000	138,500	18.6	61.8	273	285	285
5A	Center	Transverse	109,000	137,300	14.3	43.1			
2C	Midwall	Longitudinal	113,500	134,800	19.0	64.9			
2C	Midwall	Transverse	112,000	134,100	15.7	48.6			
2C	Center	Longitudinal	117,000	131,000	18.3	60.8	277	285	281
2C	Center	Transverse	115,300	134,500	14.3	47.6			
5	Midwall	Longitudinal	96,800	131,300	19.7	64.2			
5	Midwall	Transverse	101,000	130,600	17.5	51.2			
5	Center	Longitudinal	85,000	132,300	19.0	63.2	270	277	273
5	Center	Transverse	116,000	133,800	14.7	44.9			
6A	Midwall	Longitudinal	101,600	134,600	17.9	64.7			
6A	Midwall	Transverse			15.7	51.6			
6A	Center	Longitudinal	116,000	135,300	18.6	63.4	277	273	277
6A	Center	Transverse	112,000	132,500	15.0	47.6			
4C	Midwall	Longitudinal	109,000	132,800	18.3	63.4			
4C	Midwall	Transverse	105,500	130,300	17.9	52.1			
4C	Center	Longitudinal	105,000	125,800	19.3	66.2	269	266	266
4C	Center	Transverse	106,000	125,500	17.1	53.1			
4	Midwall	Longitudinal	110,000	132,500	18.6	64.2			
4	Midwall	Transverse	102,000	133,100	16.8	49.0			
4	Center	Longitudinal	116,000	135,300	18.6	63.7	277	281	273
4	Center	Transverse	116,500	135,500	15.7	48.8			
5AX	Midwall	Longitudinal	105,300	133,900	17.5	63.4			
5AX	Midwall	Transverse	109,800	131,900	17.5	51.4	273	285	285

6A	Midwall	Transverse			15.7	51.6	277	273	277
6A	Center	Longitudinal	116,000	135,300	18.6	63.4			
6A	Center	Transverse	112,000	132,500	15.0	47.6			
4C	Midwall	Longitudinal	109,000	132,800	18.3	63.4			
4C	Midwall	Transverse	105,500	130,300	17.9	52.1	269	266	266
4C	Center	Longitudinal	105,000	125,800	19.3	66.2			
4C	Center	Transverse	106,000	125,500	17.1	53.1			
4	Midwall	Longitudinal	110,000	132,500	18.6	64.2			
4	Midwall	Transverse	102,000	133,100	16.8	49.0	277	281	273
4	Center	Longitudinal	116,000	135,300	18.6	63.7			
4	Center	Transverse	116,500	135,500	15.7	48.8			
5AX	Midwall	Longitudinal	105,300	133,900	17.5	63.4			
5AX	Midwall	Transverse	109,800	131,900	17.5	51.4	273	285	285
5AX	Center	Longitudinal	112,500	136,500	17.1	61.4			
5AX	Center	Transverse	110,500	136,300	14.7	47.7			
6C	Midwall	Longitudinal	112,000	131,700	21.4	63.9			
6C	Midwall	Transverse	112,000	132,700	15.7	49.8	273	281	277
6C	Center	Longitudinal	116,500	135,500	18.3	62.5			
6C	Center	Transverse	118,000	136,300	14.7	46.4			
1	Midwall	Longitudinal	95,500	124,100	17.9	59.2			
1	Midwall	Transverse	99,500	125,300	16.4	49.4	259	273	259
1	Center	Longitudinal	101,800	129,000	17.5	57.1			
1	Center	Transverse	105,800	132,000	14.3	46.1			
2B	Midwall	Longitudinal	105,700	131,100	19.3	65.8			
2B	Midwall	Transverse	108,000	130,900	15.7	46.7	269	281	277
2B	Center	Longitudinal	111,300	131,300	18.3	61.2			
2B	Center	Transverse	114,300	133,300	15.0	43.0			
3D	Midwall	Longitudinal	107,500	132,900	19.0	63.5			
3D	Midwall	Transverse	99,000	130,800	18.6	50.4	266	281	266
3D	Center	Longitudinal	114,000	136,300	18.6	62.2			
3D	Center	Transverse	111,500	135,800	15.0	47.4			
2	Midwall	Longitudinal	112,300	134,500	19.3	63.7			
2	Midwall	Transverse	112,000	133,300	16.4	51.2	269	285	277
2	Center	Longitudinal	115,500	136,300	21.4	62.7			
2	Center	Transverse	113,300	135,500	16.4	46.8			
3B	Midwall	Longitudinal	106,500	133,100	18.6	64.5			
3B	Midwall	Transverse	104,000	132,600	16.8	49.8	269	281	277
3B	Center	Longitudinal	112,000	132,300	19.3	64.4			
3B	Center	Transverse	111,000	132,300	15.3	48.4			
1D	Midwall	Longitudinal	105,500	133,600	19.0	64.1			
1D	Midwall	Transverse	111,000	133,000	17.5	50.6	277	281	273
1D	Center	Longitudinal	115,300	136,500	18.6	61.7			
1D	Center	Transverse	115,000	135,300	15.0	47.8			

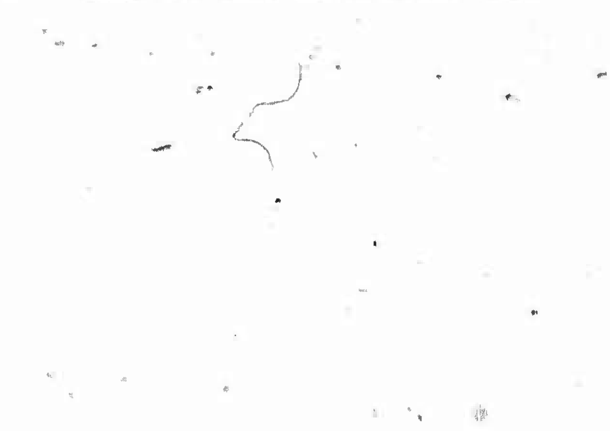
*NOTE: Midwall indicates a position halfway between the center and surface of the plate.

[1]Average of the two tests.

[illegible] Present in "Straight-Away Rolled" [illegible] Lakes Armor Plates

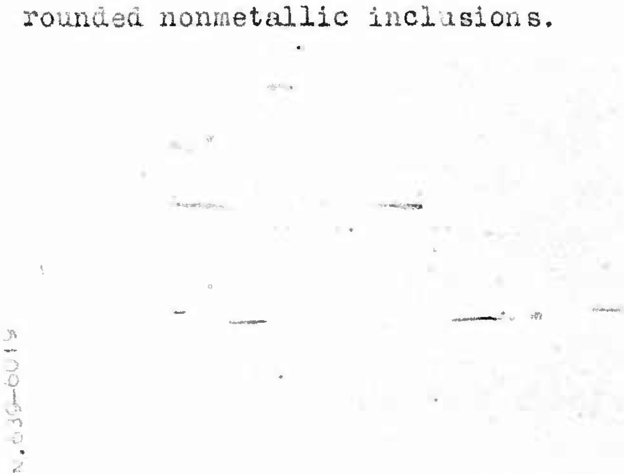
No. 3
Fine elongated nonmetallics associated with zirconium nitrides.

No. XA
Pronounced segregation of aluminum oxide.

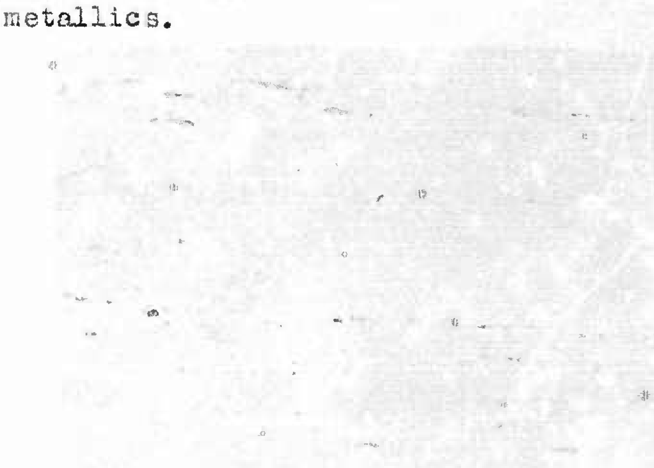


No. 1C
Fairly uniform distribution of rounded nonmetallic inclusions.

No. 6
Typical group of elongated nonmetallics.



No. 5A
Typical group of elongated nonmetallics.

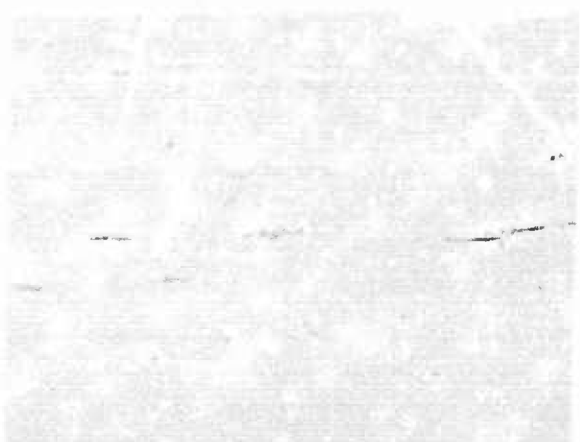


No. 2C
Typical continuous series of elongated nonmetallic inclusions.

Photomicrographs were taken on unetched longitudinal sections at a magnification of 100 diameters.

FIG. 1

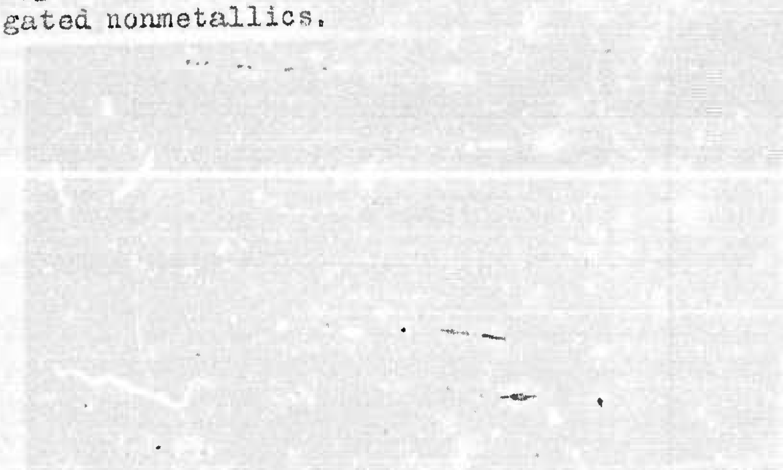
Typical Nonmetallic Inclusions Present in "Straight-Away Rolled" Great Lakes Armor Plates



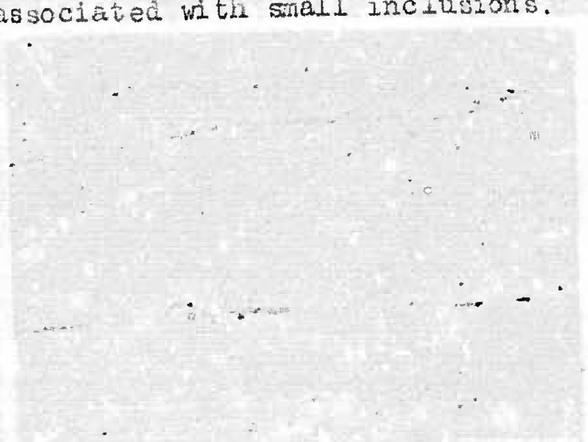
No. 5
Typical segregation of elongated nonmetallics.

No. 6A
Typical segregation of fine elongated nonmetallics.

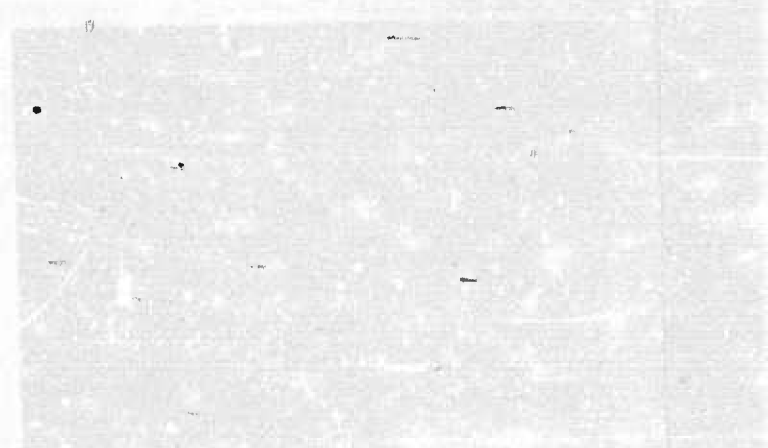
No. 4C
Typical fine elongated nonmetallics associated with small inclusions.



No. 4
Typical elongated nonmetallics.



No. 5AX
Typical elongated nonmetallics associated with fine inclusions.



No. 6C
Typical scattered nonmetallics.

Photomicrographs were taken on unetched longitudinal sections at a magnification of 100 diameters.

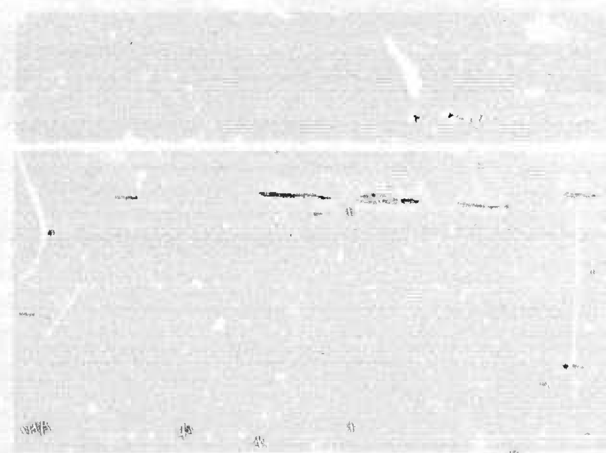
FIG 2

Typical Nonmetallic Inclusions Present in "Straight-Away Rolled" Great Lakes Armor Plates

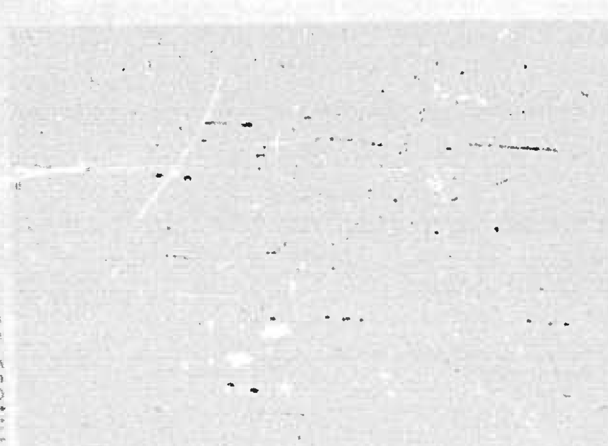
No. 1
Typical elongated nonmetallics.

No. 2B
Typical elongated nonmetallics.

No. 3D
Typical fine elongated nonmetallics.



No. 2
Typical streak of elongated nonmetallics.



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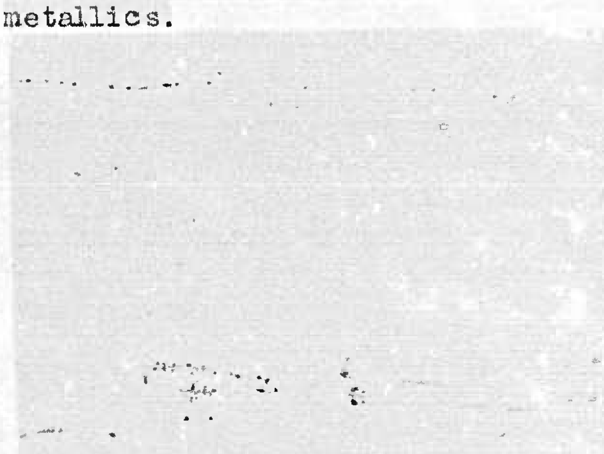
No. 3B
Typical streak of elongated nonmetallics associated with fine inclusions.

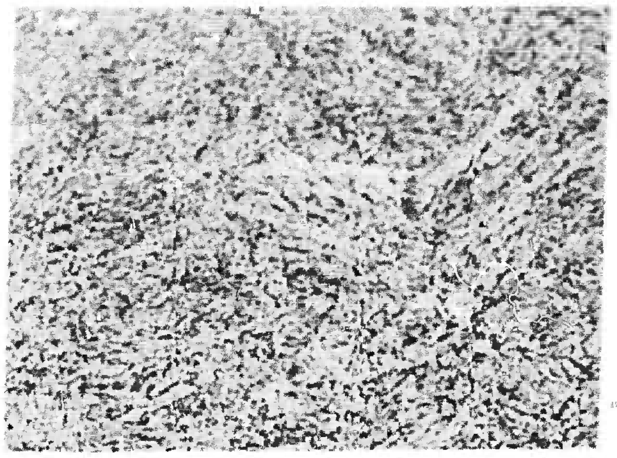


No. 1D
Typical segregation of fine elongated nonmetallics associated with zirconium nitride.

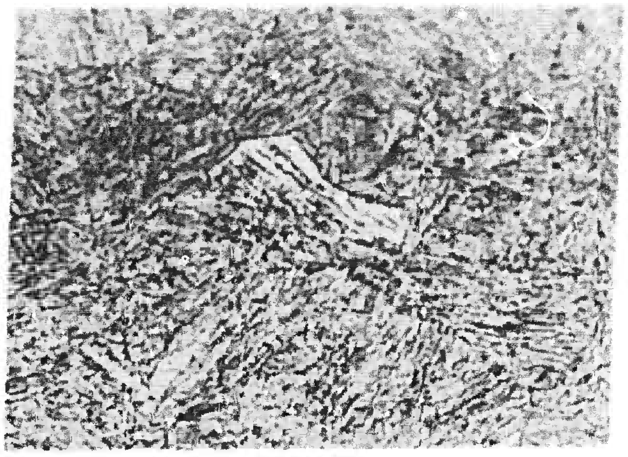
Photomicrographs were taken on unetched longitudinal sections at a magnification of 100 diameters.

FIG. 3

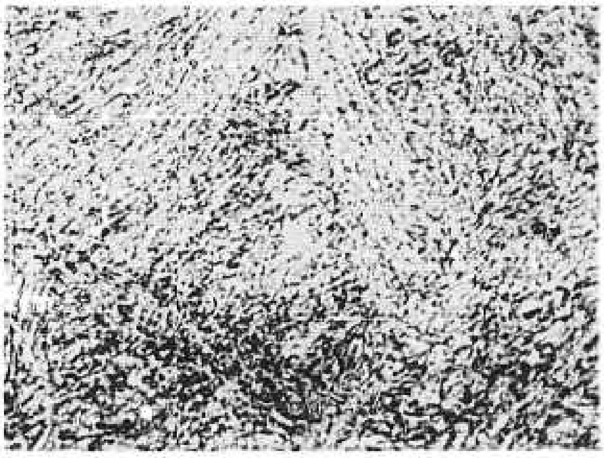
Typical Microstructure of "Straight Away Rolled"
Great Lakes Armor Plates



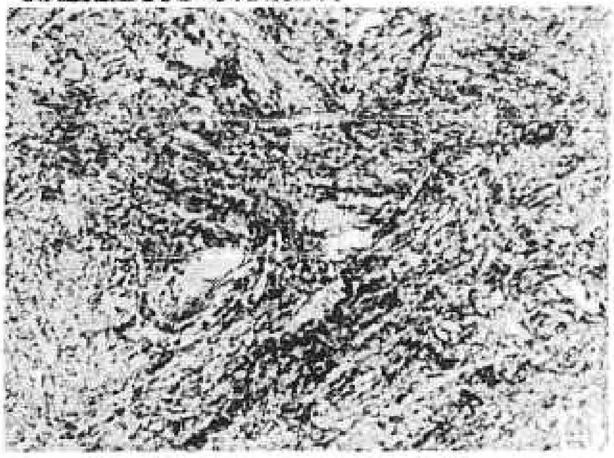
No. 3
Fairly uniform spheroidized sorbite and trace of ferrite.



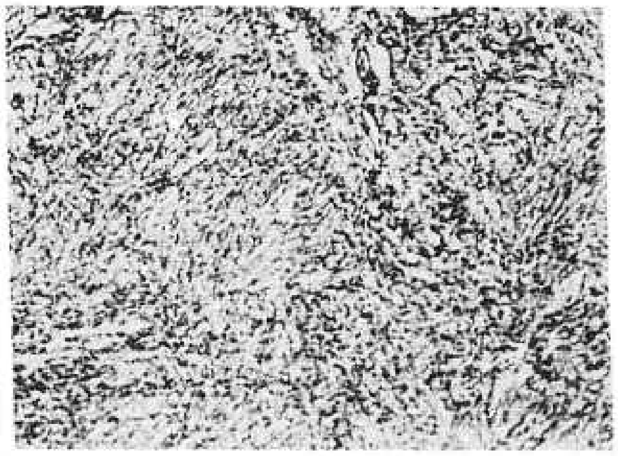
No. XA
Fine sorbite with partially dissolved carbide lamallae. Grain boundaries evident.



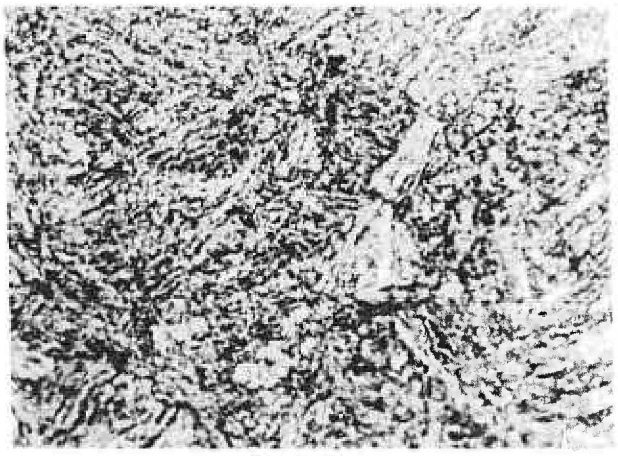
No. 1C
Sorbite.



No. 6
Sorbite, trace of ferrite.



No. 5A
Sorbite and trace of ferrite.

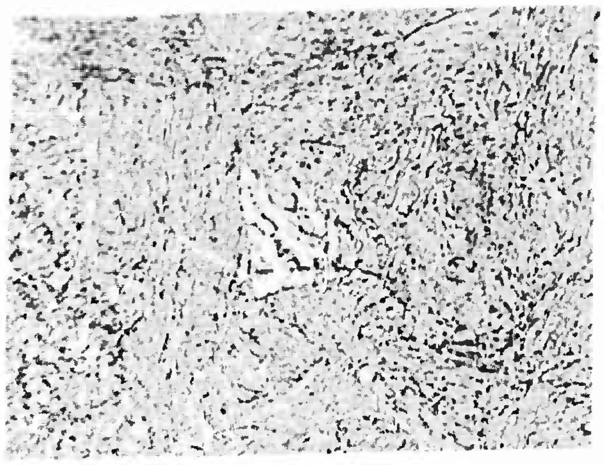


No. 2C
Sorbite and trace of ferrite.

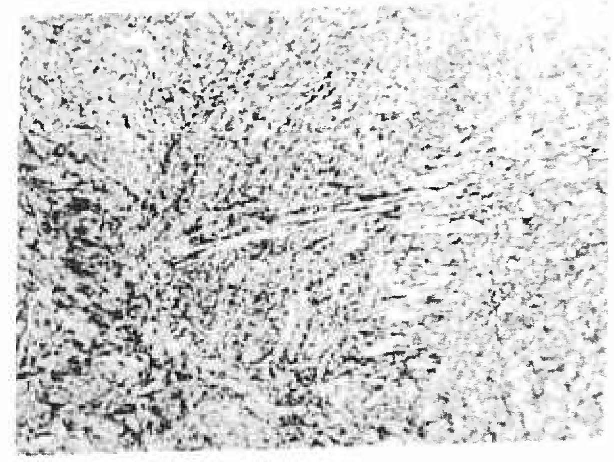
Photomicrographs were taken on picral etched longitudinal sections at a magnification of 100 diameters.

FIG. 4

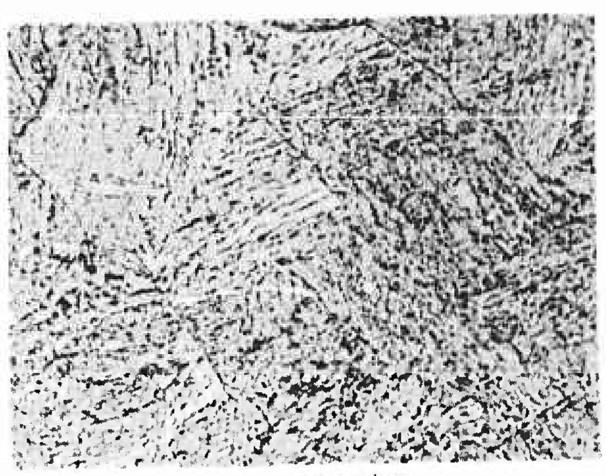
Typical Microstructure of "Straight Away Rolled"
Great Lakes Armor Plates



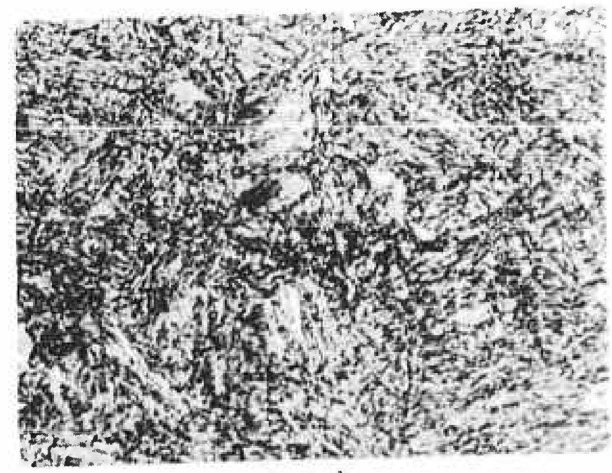
No. 5
Sorbite and trace of ferrite.



No. 6A
Sorbite and trace of ferrite.

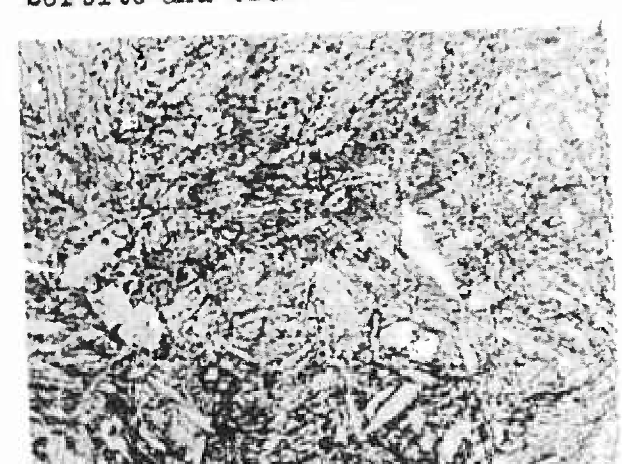


No. 4C
Sorbite and trace of ferrite.



No. 4
Sorbite and trace of ferrite.

No. 5AX
Sorbite and trace of ferrite.



No. 6C
Sorbite and trace of ferrite.

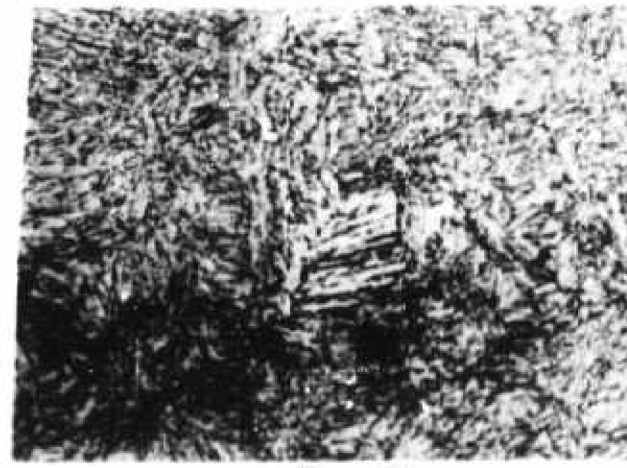
Photomicrographs were taken on picral etched longitudinal sections at a magnification of 100 diameters.

FIG. 5

Typical Microstructure of "Straight Away Rolled"
Great Lakes Armor Plates

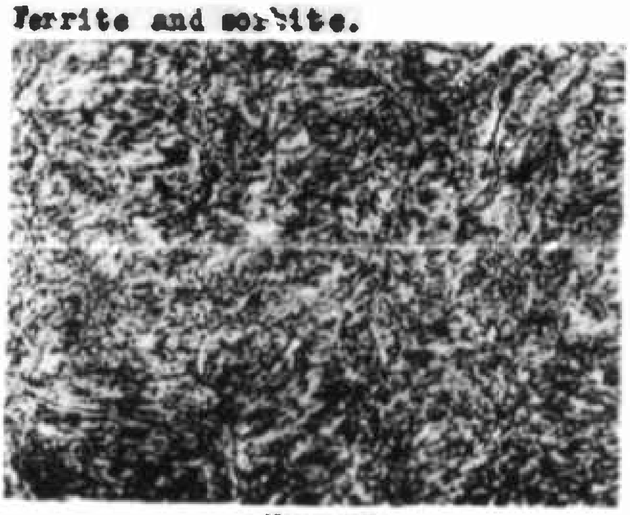
No. 1

Ferrite and sorbite.



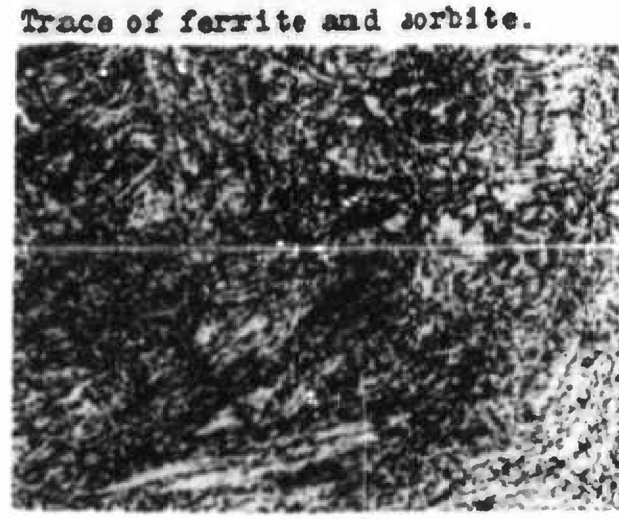
No. 2B

Trace of ferrite and sorbite.



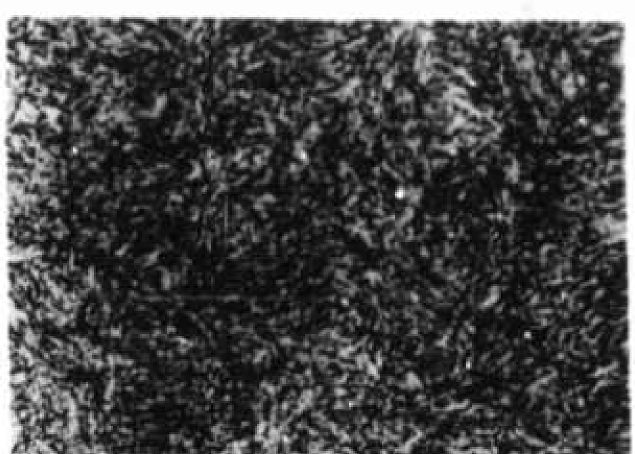
No. 3D

Fairly uniform sorbite.



No. 2

Evidence of intermediate temperature transformation products.



No. 3B

Fairly uniform sorbite.

No. 1D

Intermediate temperature transformation products.

WTN.639-6024

Photomicrographs X1000 - Picral Etch

FIG. 6